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Durability of Reinforced Concrete Incorporating Crushed Waste Brick as Coarse Aggregate

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DURABILITY OF REINFORCED CONCRETE INCORPORATING CRUSHED WASTE BRICK AS COARSE AGGREGATE

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Abstract

Using crushed bricks as aggregates in concrete is of particular interest to preserve natural aggregate sources as well as to reduce waste, as it has been estimated that 10% to 30% of all waste in landfills in the united States comes from construction and demolition wastes. By recycling some of these wastes, the sustainability of a project can be improved. However, it is important concrete incorporating these wastes is as durable or more durable then conventional concrete, or will it have a shorter service life. Durability of concrete is its ability to resist deterioration from its external environment such as physical attack, including abrasion, external loading, freezing and thawing cycles, or in the form of chemical attack, such as reinforcement corrosion. The objective of this experimental work was to study the durability of reinforced concrete made with crushed brick as partial coarse aggregate replacement. For this purpose, a comparative study was performed on the physical, mechanical, and durability properties of concrete made with crushed brick as aggregates and with natural aggregates. Results up to now show that the concrete made with natural aggregates exhibit better durability performance when compared to that made with crushed brick as aggregate. However, the poorer performance of concrete made with crushed brick is not significant and it seems it can be improved by modifying the concrete mixture. Nevertheless, this needs further investigation.

Dedication

I dedicate this to my family,

That instilled in me a passion for knowledge,

And to my instructors

For satisfying that passion.

Acknowledgements

I would like to acknowledge my advisor, Dr. Amir Poursaee, for his assistance and guidance with this work. Also, I would like to thank Dr. John Sanders and his colleagues at the National Brick Laboratory, for their assistance with this research. Finally, I would like to thank my fellow classmates Arash Razmjoo, Donald Singer, Shabi Abbas Udaipurwala, and Yujie Zhang for their help in preparing my test specimens and conducting tests.

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Introduction and Literature Review

1.1 Introduction

A growing trend in the construction industry is sustainability, which, according to the Brundtland Commission [1] is "meeting the needs of the present without compromising the ability of future generations to meet their own needs". With the increasing effects of global warming, the reduction of human impact on the planet in the form of reducing greenhouse gas emissions has become a priority. The concrete industry is perhaps one of the worst offenders, emitting an estimated five billion tons of CO_2 per year globally [2]. As a result, finding ways to reduce the carbon footprint of the concrete industry will help improve its sustainability, as well as the sustainability of all projects that incorporate concrete.

Construction and demolition (C&D) waste is estimated to constitute between 10% and 30% of all waste that enters landfills in the United States [3]. Of that debris, the dominant source by weight is asphalt, brick, and concrete, or ABC. By recycling any of these components, a demolition project will take large steps reducing the amount of waste that goes into landfills [4]. In the past, efforts have been made to recycle some of these materials as base filler for road construction and other non-structural uses [5].

When considering the possibility of recycling, many contractors think of all the reasons they should not recycle, rather the reasons they should [4]. A few of the biggest concerns planners have are: “recycling will slow down the job”; “there’s no room on site to recycle”; and, “recycling costs too much” [4]. These three perceptions are rarely true. To address the first two concerns, the key is to work a little bit smarter, not any harder or longer. Recycling containers are often color-coded or labeled, making the sorting of waste easy and fast, provided the proper containers are on-site and strategically placed. It is not necessary to have several containers on site at a time, but only the containers that are necessary for each phase of the demolition. It has also been shown that workers support recycling, and as a result, morale is boosted and productivity increases. The third concern about cost increase is also oftentimes false, though this can depend on the location of the site. Figure 1.1 shows the estimated cost of recycling various types of C&D waste by ton, along with the average transportation cost for each type by ton [4]. The bottom bar in the figure illustrates the cost of landfilling these materials. It can be seen that, for example, recycling one ton of concrete, brick, and block costs approximately $21.00, while landfilling one ton of the same would cost approximately $136.00.

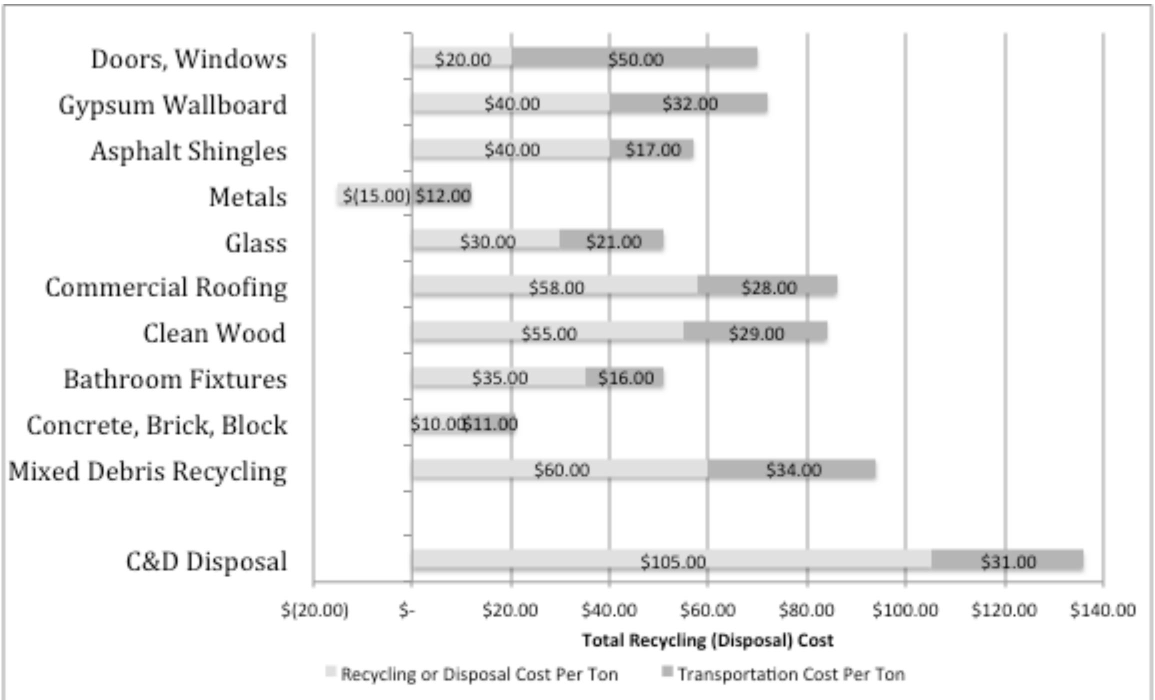

Figure 1.1: Boston area cost of C&D recycling vs. disposal [4]

It seems that, the use of recycled C&D in concrete will depend on the availability of the conventional aggregate sources versus these materials in the regional or local construction market. As landfill space and virgin aggregate become more costly in some markets in the United States [6], it is likely that use of recycled aggregates including C&D in concrete applications will increase as well.

1.2 The use of waste brick as aggregate in concrete

Using crushed bricks as aggregates in concrete is of particular interest to preserve natural aggregate sources as well as to reduce waste and waste storage. The first use of crushed brick with portland cement was recorded in Germany 1860 for the manufacturing of concrete products [7, 8], but the first significant use of crushed brick as aggregates in new concrete has been recorded for reconstruction after the Second World War [9]. Brick masonry has long been used as a reliable building material in the United States, and is a popular material used in South Carolina today. Every year, the United States produces approximately nine billion bricks. According to an industry survey, of those nine billion bricks, 11.4 kg/ton are dumped in landfills and are not recycled back into production [10]. One solution to this problem could be recycling the waste bricks, either excess new bricks, or waste from demolished structures, and using them as aggregates in concrete.

Generally, lack of knowledge of performance of brick aggregate concrete is an obstacle for reuse of brick waste [11]. However, with increased environmental awareness during the past decades and economic motivations to re-use waste, use of masonry rubble is once again receiving attention from the technical community. The use of masonry rubble in non-structural applications such as paving blocks is of interest of many countries and many studies have been conducted on this application, worldwide [12-18]. In most of the studies, bricks have been used as both fine and coarse aggregate substitutes, and as partial and complete substitutes for natural aggregates [19-23].

1.2.1 Properties of Bricks and Brick Aggregates

From the information gathered, it is apparent that the porosity and absorption of brick aggregates is higher than that of most of the natural aggregates, and due to this high porosity and absorption, it is suggested to soak the brick aggregates in water prior to adding to the concrete mix [19, 20, 24].

From Table 1.1, it is also clear that not all bricks are created equal.

Variations in the compressive strengths of bricks are not only due to different types and manufacturing methods of bricks, but also due to impurities that are part of the nature of recycled aggregates. When buildings are demolished, for example, several impurities get into the brick rubble, such as paper, plastic, timber, glass, concrete, metal, and most critically, mortar [19]. If bricks were to be used as a substitute for natural aggregates in concrete, quality control measures will be necessary to ensure that bricks being use satisfy strength requirements.

Table 1.1: Types of brick/aggregate used in investigation with results of tests on both materials [19]

								Water absorption of brick unts (%)		Water absorption of 20 mm lumps (%)	
Brick/Aggregate Type	Full-brick compressive strength (N/mm^2)	Coefficient of variation (%)	Half-brick compressive strength (N/mm^2)	Coefficient of variation (%)	Aggregate impact value (%)	Aggregate relative density (SSD)	Aggregate porosity (%)	5-hour boil	24-hour soak	5-hour boil	24-hour soak
Common solid-solid brick	39	6.6	43	3.2	31	1.97	25.04	12.9	10.3	14.1	11.5
5-slot perforated brick	59	5.8	65	7.3	25	2.22	20.08	10.7	9.5	13.8	12.4
3-slot perforated brick	68	5.2	79	9	19	2.20	17.39	5.8	5.3	7.4	7.4
10-hole perforated brick	81	3.3	84	7.3	19	2.25	16.75	6.2	4.6	7.4	7.4
Eng B solid-solid wire cut facing brick	92	6.6	106	7.8	14	2.41	14.85	6.0	5.2	6.3	6.2
Recycled wash aggregate	–	–	–	–	24	2.18	14.49	–	–	12.7	10.4
Recycled masonry aggregate	–	–	–	–	33	1.94	24.44	–	–	19.8	16.2
Granite aggregate	–	–	–	–	9	2.85	6.15	–	–	2.63	2.55

1.3 Properties of Concrete Incorporating Crushed Brick Aggregate

1.3.1 Strength

Previous studies, show that the use of brick aggregate as a substitute for granite aggregate results in a loss of compressive strength [19, 20, 22, 23]. In general, this loss of strength is to the order of 10 – 35% for coarse aggregates, and

30 – 40% for fine aggregates, depending on the rate at which the brick was substituted for natural aggregates, as can be seen in Figure 1.2. However, with this decrease in compressive strength, a gain of about 11% is made for tensile strength, compared to normal weight concrete [21].

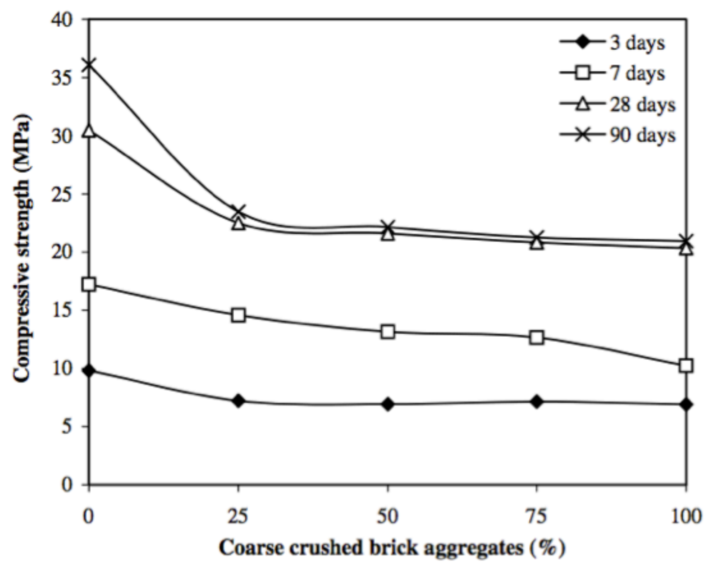

Figure 1.2: Concrete compressive strength versus coarse crushed brick aggregates substitution [22]

Another consensus amongst the studies is that new bricks, due to advances in brick making technology and their lack of impurities, are better parent for brick aggregate. It is shown that the 28-day compressive strength of normal-strength concrete made with this brick exceeded that of normal-strength concrete made with natural granite aggregate. For high-strength concrete, these values were virtually identical [20].

1.3.2 Absorption

The water absorption of crushed brick is relatively high compared to natural aggregates [25]. As a result, it is recommended that aggregates should be considered to be in saturated condition when preparing a mix design [20]. Figure 1.3 shows the change in water absorption of concrete based on the replacement of natural aggregate with brick aggregate.

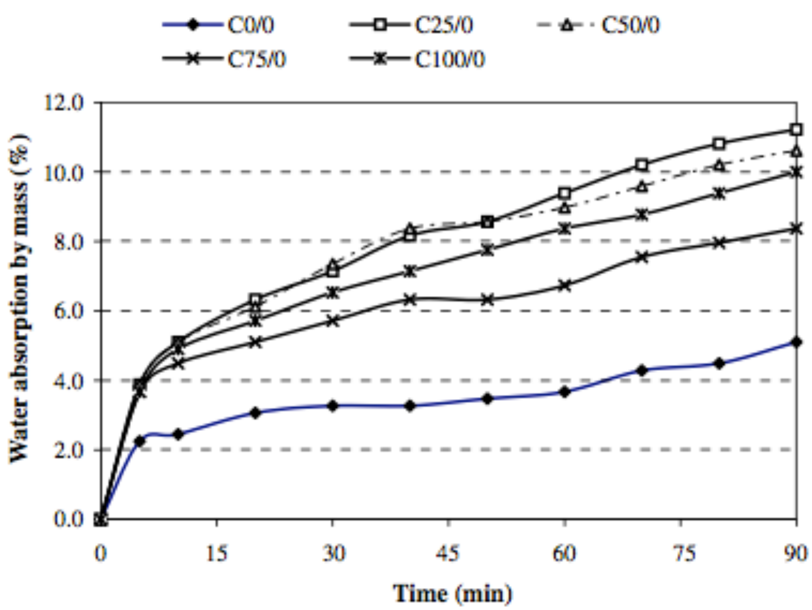

Figure 1.3: Water absorption of concrete made with coarse crushed brick as aggregate [22]

1.3.3 Freeze-Thaw

Relatively little work has been done in durability concerns related to brick aggregates in concrete. Many researchers are reluctant to use any crushed bricks as aggregate in concrete due to concerns about their durability performance. While the high porosity of brick particles contributes to higher permeability, the porosity of the particles can potentially improve the performance in freeze-thaw testing. Most studies in this area have been performed on very small brick particles used as a partial replacement for fine aggregate. Litvan and Sereda found that incorporation of small brick particles (0.4 mm to 0.8 mm) with high porosity to mortar and concrete mixtures improved the freeze-thaw resistance of the mixtures [26]. Bektas et al. performed tests on crushed brick used as a partial replacement for fine aggregate and indicated that "the highly porous nature of crushed brick might provide a similar air entraining action and reduce the freeze-thaw expansion" [27]. Another study by Mulheron and O'Mahony on concrete, partially made with clay brick as aggregate, concluded better freeze-thaw performance that that of concrete made with natural aggregates [28, 29].

1.3.4 Chloride Penetration

One of the most important causes of corrosion in concrete reinforcement is the result of depassivation of the steel due to the ingress of chloride ions [30]. As a result, it is important to consider a concrete's ability to resist chloride penetration. There are many different techniques that can used to measure chloride penetration. However, the number of studies on the chloride diffusion into concrete made with brick aggregates is very limited. Kibriya and Speare [31]studied the chloride ion diffusion in brick aggregate and natural aggregate concrete mixtures and found that the chloride diffusivity of the brick aggregate concrete mixtures were greater than the control natural aggregate mixture. On the contrary, the result of the tests conducted by Cavalline showed that the brick concrete mixtures exhibit fairly good results in chloride ion permeability testing [32].

One of the more simple techniques to identify the chloride ingress into concrete is to use a 0.1N silver nitrate solution ($AgNO_3$) [33-35]. This technique involves taking a freshly broken piece of concrete and spraying the cross-section, perpendicular to suspected flow of chlorides, with the silver nitrate solution. The areas that turn a purple or pink color indicate chloride contamination. If this color change is detected, it can be assumed that the steel reinforcement exposed to this depth is at risk of corroding. This approach is used in this research to study the ingress of chlorides into concrete made with natural and brick aggregates.

1.4 Corrosion of Steel Reinforcement in Concrete

As mentioned before, the major cause of corrosion in steel reinforcement is considered to be chloride ions. The chloride ions can be mixed into the concrete unintentionally, or dissolved chlorides can penetrate the concrete exposed to deicing salts or marine environments. The rate of corrosion is further influenced by the environment within the concrete, specifically the availability of moisture and oxygen [36].

The corrosion of the steel reinforcement is an electrochemical reaction. Small regions of the surface of the rebar act as the anode and cathode, and are connected by the rest of the steel, with the pore solution of the concrete acting as the electrolyte. The resulting corrosion products are larger than the steel they were derived from, thus causing internal expansive stresses. Eventually, these stresses will crack the concrete, exposing the rebar to more aggressive environments, and accelerating the corrosion rate [37]. As mentioned before, the majority of the studies on replacing natural aggregates with crushed brick in concrete were focused on non-structural concrete. As a result, as far as the author concerns, no research was carried out on the impact of using crushed bricks as aggregates in concrete and corrosion of steel bars.

1.5 Problem Statement and Scope of Work

Construction and demolition waste constitutes an estimated 10% to 30% of all waste that goes into American landfills annually [3]. By recycling that waste as aggregate in concrete, it is possible to improve the sustainability of the concrete industry. This study sought to explore the feasibility of used crushed brick as aggregate in reinforced concrete. This was determined by comparing both mechanical and durability properties of concrete made with natural granite aggregate to concrete made with partial coarse aggregate replacement with brick aggregate.

1.6 Objectives

The objective of this study was to determine the durability of reinforced concrete incorporating crushed brick as aggregate. This was done by comparing the mechanical and durability properties of concrete with 100% natural granite aggregate, 25% coarse brick aggregate, and 50% coarse brick aggregate. Properties examined included: compressive strength, freeze/thaw durability, chloride penetration, electrical resistivity, and corrosion resistance.

Chapter 2

Materials and Methods

2.1 Aggregate Information

Due to high water demand demonstrated in concrete mixtures incorporating fine crushed brick as aggregate and based on previous results in the literature [10, 24], partial coarse aggregate replacement was chosen at in this study.

A flat graded coarse aggregate was chosen rather than blending the sizes to a particular grade aggregate. This would also guarantee uniformity in aggregate size in all samples.

1. Natural coarse aggregate used came from Liberty, South Carolina.
2. Brick aggregate was obtained by crushing new bricks obtained from General Shale, in Anderson, South Carolina. Since this study is relatively new and mainly considered a proof of concept, new bricks were chosen for use in this study. The next step would be using bricks from landfill.

2.2 Production of Crushed Brick Aggregate

A crushing apparatus that uses a reciprocating jaw, Figure 2.1, was used in the production of the crushed brick aggregate. Whole new bricks were broken in half by a brick hammer, and dropped into the machine. The crusher used was developed for research purposes at Clemson University's National Brick Research Institute, and therefore is not intended for industrial application, and thus can only receive a limited volume of material at a time. The product was collected in buckets and later separated by sieve size.

Figure 2.1: Crushing apparatus for production of brick aggregate

2.3 Physical Properties of Aggregates

2.3.1 Natural Aggregate Properties

The natural aggregates from Liberty South Carolina, were sieved and the half-inch portion was used as the aggregate in the mix design. The specific gravity and the absorption of the aggregate was determined using ASTM C 127 [38]. The aggregates were first oven dried at 110°C until a constant weight was achieved, which took 48 hours. The aggregate was then soaked for 24 hours in a water bath. After soaking, the aggregates were surface dried with a towel and weighed. The aggregate was then immediately placed in a sample container and the mass was determined suspended in water. The aggregate was again oven dried at a temperature of 110°C until a constant mass was achieved, which took 72 hours, and the mass was recorded. The following equations were used to calculate the properties of the natural aggregate:

$$SG_{OD} = W_{OD}/(W_{SSD} - W_{SW}) \qquad \text{Equation. 2.1}$$

where SG_{OD} is specific gravity (oven-dry), W_{OD} is oven-dry weight, W_{SSD} is saturated surface dry weight, and W_{SW} is weight suspended in water

$$SG_{SSD} = W_{SSD}/(W_{SSD} - W_{SW}) \qquad \text{Equation 2.2}$$

where: SG_{SSD} is specific gravity (saturated surface dry),

OD and SSD densities can then be calculated using equations 2.3 and 2.4, respectively:

$$\text{Density, OD} = 997.5 \times SG_{OD} \ \ (kg/m^3) \qquad \text{Equation 2.3}$$

$$\text{Density, SSD} = 997.5 \times SG_{SSD} \ (kg/m^3) \qquad \text{Equation 2.4}$$

Absorption determined using equation 2.5:

$$\text{Absorption, \%} = [(W_{SSD} - W_{OD})/W_{OD}] \times 100 \qquad \text{Equation 2.5}$$

2.3.2 Brick Aggregate Properties

The bricks that were used for aggregates were obtained new from General Shale, in Anderson, South Carolina. New bricks were chosen for this study because of the ready supply (so more of the exact same brick could be obtained if needed), consistency, and lack of possible contaminants. After crushing, the aggregate was sieved and the portion passing the half-inch sieve and retained on the 3/8–inch sieve was used as coarse aggregate in concrete.

After crushing the bricks, a sieve analysis was performed on one of the buckets that contained the raw crushed bricks. The analysis is shown in Table 2.1, and can be used to determine what quantities of raw brick may be needed to acquire a particular gradation.

Table 2.1: Sieve analysis of raw crushed bricks

Sieve No.	Percent Retained	Percent Coarser	Percent Finer
1"	0.13%	0.13%	99.87%
3/4"	2.22%	2.35%	97.65%
1/2"	16.04%	18.39%	81.61%
3/8"	22.09%	40.48%	59.52%
No. 4	28.81%	69.28%	30.72%
No. 8	12.18%	81.47%	18.53%
No. 16	7.32%	88.79%	11.21%
No. 30	4.24%	93.03%	6.97%
No. 50	2.44%	95.47%	4.53%
No. 100	1.12%	96.59%	3.41%
Pan	0.24%	96.83%	3.17%

The compressive strength of the brick aggregate was determined by finding the compressive strength of the parent brick. The test was performed in accordance to ASTM C 67 [39] As required by the ASTM standard, the whole bricks were cut into two pieces, one piece to be used for the compressive strength test, and the other to be used for the absorption tests. The section used to test the compressive strength was approximately one-half to one inch greater than half the original length of the brick.

The bricks were then dried for 24 hours in an oven at 110°C. After drying to consistent weight, the bricks were cooled in a ventilated room to a temperature of about 25°C. The brick specimens were then capped using sulfur conforming to ASTM C 67 and in the specified manner (Figure 2.2). After capping, the brick compressive strength was determined.

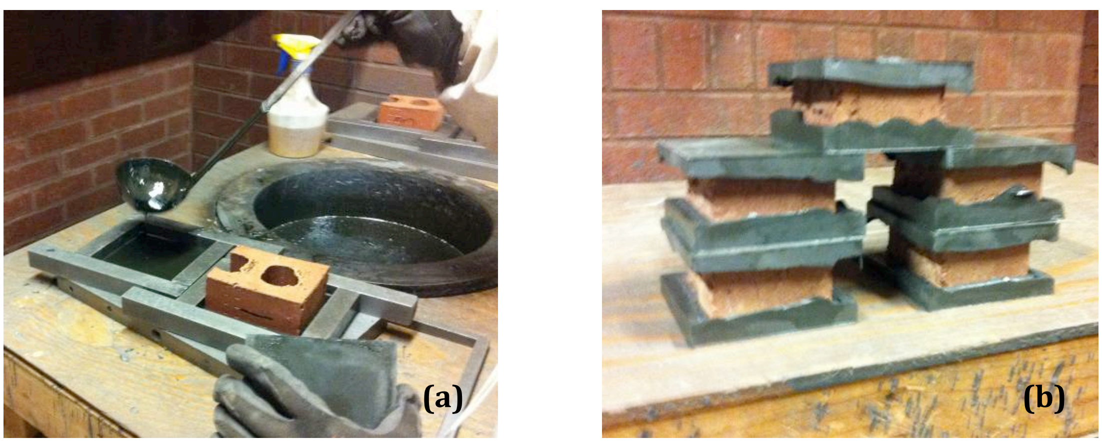

Figure 2.2: (a) Sulfur-capping of brick specimens for compressive strength test, and (b) Sulfur-capped test specimens

The absorption of the brick aggregate was determined by measuring the absorption of the parent brick, using ASTM C 67 [39] For this procedure, the second section of brick that was remaining after the compressive test was used. The test samples were dried and cooled in the same manner as was described for the samples for compressive testing. After drying, an initial weight was taken. The samples were then subjected to a cold-water absorption test, in which they were placed in a bath of water for a 24-hour time period and left in a room at room temperature (Figure 2.3). The samples were removed, surface dried, and weighed. The cold-water absorption was determined using the following equation:

$$\text{Absorption, \%} = 100(W_s - W_d)/W_d \qquad \text{Equation 2.6}$$

where: W_s is saturated weight and W_d is oven dry weight

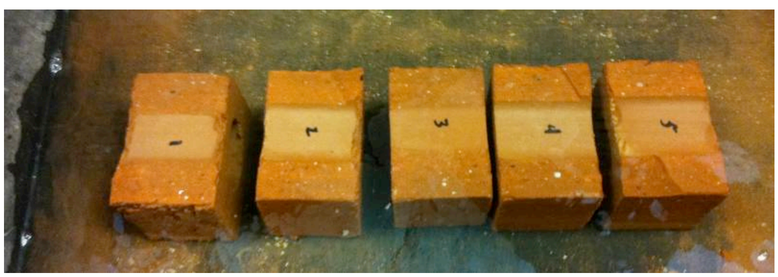

Figure 2.3: 24-hour cold-water absorption test, water bath

Following the cold water absorption test, the samples were then subjected to a 5-hour boiling water absorption test. The samples were transferred, in their saturated condition, to a pot of water on a gas stove, and boiled for 5 hours (Figure 2.4). After the specified duration of time, the samples were allowed to cool back down to room temperature in the water bath through natural loss of heat. The samples were then surface dried and weighed, and the boiling-water absorption was determined using the equation 2.7:

$$\text{Absorption, } \% = 100(W_b - W_d)/W_d \qquad \text{Equation 2.7}$$

where: W_b is weight after boiling

Figure 2.4: 5-hour boiling-water absorption test, set-up

The cold-water and boiling-water absorption of the brick aggregates were determined to be 1.61% and 1.80%, respectively.

The specific gravity and density of the aggregate was determined using ASTM C 127 [38], as explained for the natural aggregates.

2.3.3 Abrasion Resistance of Natural and Brick Aggregates

The abrasion resistance of the coarse aggregates was determined according to ASTM C 131 [40] L.A. Abrasion for small size coarse aggregate, and aggregate gradation C was chosen. Aggregate gradation C requires eight steel charges. After washing and drying, the aggregates were combined in the specified gradation for samples that included: 100% granite aggregate, 25% brick aggregate, 50% brick aggregate, and 100% brick aggregate. The aggregate samples were then placed in the L.A. abrasion machine with the steel charges (Figure 2.5). The uniformity test was performed on all the samples. This test required that the samples be stopped, sieved, and weighed after 100 revolutions, before the completion of the standard 500 revolutions. The samples were sieved on the number 12 sieve after 100 revolutions, and the coarser material was weighed. All of the material, coarser and finer than the number 12 sieve was returned to the abrasion machine for the remaining 400 revolutions. The sieving was repeated and the aggregate remaining above the number 12 sieve was washed and placed in an oven at 110°C for 48 hours, after which it was weighed. The following calculations were used:

$$\text{Loss, \%} = (W_0 - W_{500})/W_0 \qquad \text{Equation 2.8}$$

Where: W_0 is initial weight of sample and W_{500} is weight coarser than No. 12 sieve after 500 revolutions.

The uniformity ratio was then calculated by using Equation 2.9:

$$UR = W_{100}/W_{500} \qquad \text{Equation 2.9}$$

Where: UR is uniformity ratio and W_{100} is weight coarser than No.12 sieve after 100 revolutions.

Figure 2.5: L.A. abrasion apparatus

2.4 Cement

Argos Type I/II cement was used in all concrete batches. The cement was produced in Harleyville, South Carolina. The phase composition (ASTM C 150[14]) of the cement is:

- C3S (%) - 58
- C2S (%) - 16
- C3A (%) - 8 (8 max)
- C4AF (%) - 10

Cement Mill Certificate is shown in Appendix II.

2.5 Mix Design

The mixture proportions were determined by volume, with coarse aggregate composing 35%, fine aggregate 25%, water 23%, and cement 17%, resulting in a water-to-cement ratio of 0.42. Three separate types of concrete were made with varying blends of coarse aggregate. They include:

1. 100% natural granite aggregate
2. 25% crushed brick aggregate / 75% natural granite aggregate
3. 50% crushed brick aggregate / 50% natural granite aggregate

100% natural granite aggregate was chosen as the control sample that all other results would be compared against. 25% brick and 50% brick aggregate replacement was chosen due to the results in previous studies [10, 24]. The batch weights used are shown in Table 2.2.

Table 2.1: Batch weights per cubic yard of concrete

Material	Control Batch Weight (lbs/yd^3)	25% Brick Batch Weight (lbs/yd^3)	50% Brick Batch Weight (lbs/yd^3)
Cement (Type I)	914	914	914
Water	399	399	399
Fine Aggregate	1036	1036	1036
Natural Coarse Aggregate	1462	1097	731
Brick Coarse Aggregate	0	392	784

2.5.1 Mixing

Since the brick aggregate has a relatively large absorption rate, it was decided that the coarse aggregates would be added to the mix in a saturated surface dry condition in order to maintain a constant w/c ratio. This was achieved by soaking the coarse aggregates in water for a period of a week prior to mixing. Then, the aggregates were transferred to buckets that had holes drilled in the bottom, and allowed to drain for a period of 12 hours prior to mixing. During the draining process, the buckets were covered with lids with a single hole drilled in it to prevent evaporation off the top. Prior to mixing, the aggregates were removed from the buckets and weighed out and combined in the proper proportions.

The fine aggregate was oven dried at 110°C for 48 hours prior to mixing, and allowed to cool to room temperature for approximately 3 hours.

The concrete aggregates, cement, and water were then combined and mixed in a drum mixer in accordance with ASTM C 192 [41]. The concrete was mixed for three minutes, allowed to rest for three minutes, and then mixed again for a final two minutes. The concrete was then removed from the mixer and placed in the molds for the various types of specimens required for each test.

2.6 Specimens

Various types of specimens were required in this project. Specimens were included cylinders, corrosion prisms, freeze/thaw specimens and cylinder for electrical measurements.

2.6.1 Cylinders

A total of fourteen 4-in × 8-in cylinders were cast for each sample type. These cylinders were made in accordance with ASTM C 192 [41]. The concrete was scooped into the cylinders to half-full, tamped 25 times, filled to over-full, and then tamped 25 more times. The surface was then finished with a metal trowel. After covering the cylinders with a plastic cap to prevent evaporation and allowing them to set overnight, the cylinders were demolded and placed in the curing room at 100% relative humidity to cure.

2.6.2 Corrosion Samples

A total of three corrosion samples were made for each sample type. A modified ASTM G 109 [42] mold was created for these samples. Instead of creating samples according to the standard and building a Plexiglas reservoir on the top, the reservoir was molded into the sample. This was achieved by increasing the height of the mold to that of the sample height plus the height of the reservoir. A block of wood was then cut to the dimensions of the reservoir, and attached to the bottom of the mold (the samples were placed upside-down).

The rebar that was used in the samples were power wire brushed to remove any rust that may be present on the steel. The rebar was then drilled and tapped, allowing for the insertion of threaded rod in one end, on which wires could be connected to the sample. A two-part epoxy coating was applied to each rebar, with an eight-inch section in the middle left uncoated. By coating the ends and leaving a section exposed in the middle, it was possible to control the amount of steel in each specimen that is susceptible to corrosion. Since the rebar was protruding from the specimens on each side, coating the ends prevented galvanic corrosion as the result of differential environments. The eight-inch section in the middle allowed the rebar directly under the reservoir to corrode. The rebar was placed in the molds and concrete was placed in the mold in fourths. The concrete was tamped and very briefly vibrated to ensure proper consolidation around the reservoir on the bottom of the mold and around the rebar. The surface was finished with a metal trowel and covered with damp towels to prevent evaporation. After a 24-hour setting period, the samples were placed in the moist room at 100% humidity for curing. One of the corrosion samples is shown in Figure 2.6.

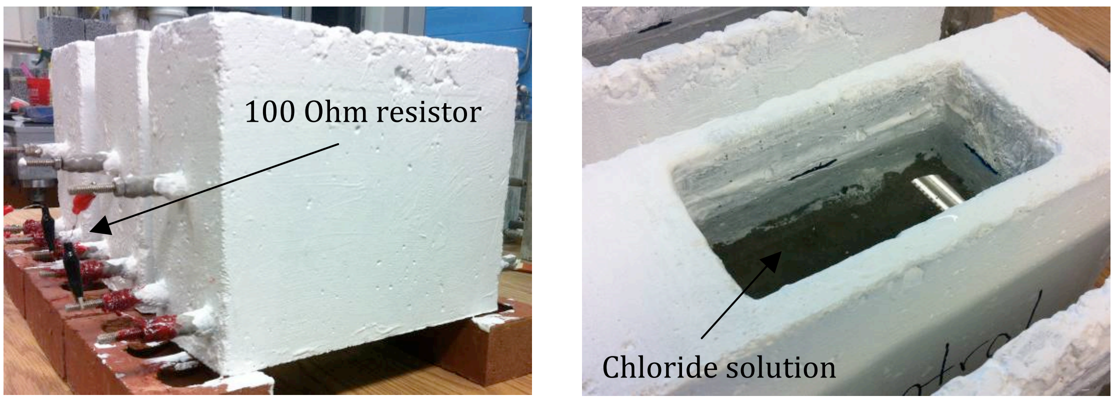

Figure 2.6: Modified G109 samples

2.6.3 Freeze/Thaw Samples

A total of three 3-in × 3-in × 12-in freeze/thaw samples were made for each sample type, in accordance with ASTM C 666 [43]. The samples were filled in thirds and tamped with a hard rubber tamper.

2.6.4 Electrical Resistance Samples

A total of three 4-in × 8-in cylinders were poured for each of the sample types. A 0.25-in piece of plastic was placed in the bottom of each mold, and two holes were drilled and threaded in each one which allowed for the insertion of 5/16-in threaded stainless steel rods. These rods were placed at three inches apart on-center, and half-inch on-center from the sides. One cylinder was poured for the control sample that contained a thermocouple. Figure 2.7 shows the insert was casted into each sample and a schematic of each sample.

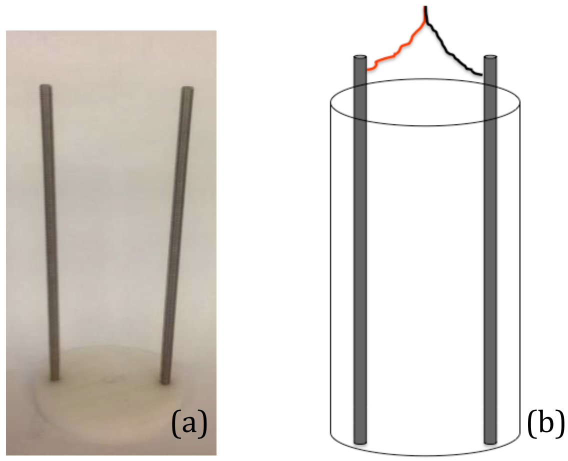

Figure 2.7: (a) Stainless steel rods that was molded into 4-in × 8-in cylinder and (b) schematic illustration of one of the samples for the electrical resistance measurement

2.7 Experimental Procedures

2.7.1 Workability

The workability of fresh concrete was measured using the slump test, in accordance with ASTM C 143 [44].

2.7.2 Concrete Compressive Strength

The compressive strength of each of the three types of concrete mixes was determined by ASTM C 39 [45]. Three samples were tested of each type at 28-day strength, and the results were averaged.

2.7.3 Freeze/Thaw

The freeze/thaw test was conducted with a modified ASTM C 666 [43], Procedure A. For this method, the 3-in × 3-in × 12-in specimens were submerged under 1/8-in of water during the freezing cycle. The test was performed at the Clemson University's National Brick Research Center, in a custom-made freeze/thaw chamber. This chamber consists of a walk-in freezer, in which the sample containers are placed on shelves. The containers each hold three samples, sitting side-by-side, with approximately 0.5-in between each sample. On the bottom of the container is a heat pad used for the thawing process. Using a thermocouple, located under the center sample in each container, the system monitors when the samples have reached the target freeze temperature, and the heating pads are turned on to thaw out the sample. The same thermocouple is used to determine when the sample has reached its target thaw temperature, at which time the heat pad is turned off and the sample is again allowed to freeze. Figures 2.8 and 2.9 show the freezer used for the freeze and thaw testing and a specimen container and a specimen, respectively.

Figure 2.8: Freeze/Thaw chamber at Brick Center

Figure 2.9: (a) Specimen container and (b) one of the specimens for freeze/thaw test

2.7.4 Density, Absorption, and Voids of Hardened Concrete

The physical properties of the hardened concrete mixes were determined using ASTM C 642 [46]. For this test, cylindrical samples four inches in diameter and two inches in height were cut from 4-in × 8-in cylinders of each mix type. A total of three of these samples were tested for each type and the average of the three were taken.

2.7.5 Corrosion

Corrosion of steel reinforcement for each concrete mix was examined using ASTM G 109 [42]. The samples were elevated by placing bricks under each end of the samples, allowing approximately two inches of clearance for air to flow underneath. The samples were coated with three coats of waterproof sealer. The cycling rate of two weeks wet, two weeks dry was used, according to the standard, but a sampling rate of one week was chosen as apposed to monthly. A 100 ohm resistor was connected between top and bottom rebars. In addition, both bottom bars were connected together, which enhances the corrosion on the top rebar. By measuring the voltage across the resistor using a high impedance voltmeter, macro-cell corrosion current density can be calculated using Ohm's law. In macro-cell corrosion, anodic reaction, (oxidation of steel) happens at the top rebars while cathodic reaction (reduction of oxygen) occurs at the surface of the bottom rebars. Using this test method, the corrosion activity of different mixtures can be evaluated.

Additionally, half-cell potential measurements were made according to ASTM C 876 [24]. The half-cell potential or corrosion potential is the most widely monitored parameter to assess the condition of steel in concrete, particularly in the field. The potential is a thermodynamic measure of the ease of removing electrons from the metal in steady state condition. For these measurements, a calomel reference electrode was used. However, since ASTM C876 criteria for accessing corrosion is based on $Cu/CuSO_4$, all the measurements were converted to $Cu/CuSO_4$ reference electrode. After the G109 measurements, the 100-ohm resistors were disconnected for 24-hours and then the half-cell potential measurements were made. For periods when the reservoir on top of the specimen was filled, the reference electrode was placed in the reservoir and connected to the negative node of the voltmeter, and the positive node was attached to the top reinforcement bar. For dry periods when the reservoir was empty, a wet sponge was placed in the reservoir and the electrode was pressed against it, to allow for a strong connection between the electrode and the surface of the concrete.

2.7.6 Chloride Penetration

For additional information regarding the penetration of chlorides into the corrosion samples, three 4-in × 8-in cylinders were cut in half, and coated and elevated in the same manner as the G109 samples. A reservoir was then constructed on the top of the cylinder halves out of aluminum tape, and the inside edges were coated with waterproof sealer to prevent leaks. The samples were then subjected to the same wet/dry cycling that the corrosion samples were exposed to. Figure 2.10 shows one of the samples for this test. Each month, at the end of each dry cycle, one cylinder was split and the exposed surface was sprayed with 0.1 N silver-nitrate solution [34]. After 24 hours, the chlorides turned a purple color, and the depth of penetration was recorded. It was assumed that this depth of penetration coincided with the depth of penetration in the corrosion samples.

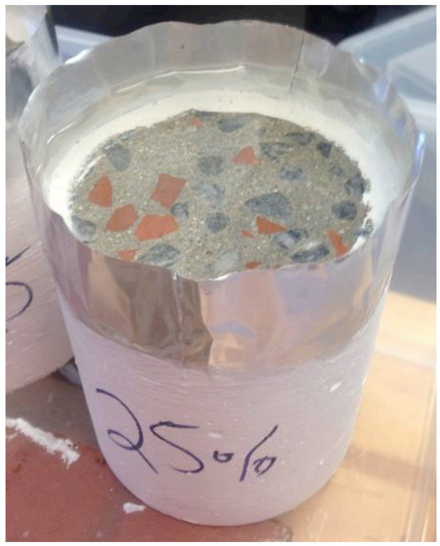

Figure 2.10: One of the chloride penetration samples, containing 25% brick, with aluminum tape reservoir, containing salt solution

2.7.7 Electrical Impedance

Electrical impedance measurement techniques have been shown to provide useful information that can be used to characterize cementitious systems [47-49]. This technique studies the system response to the application of a small amplitude alternating potential signal at different frequencies. AC electrical impedance measurements have the advantages of being non-invasive and non-destructive, require little in term of preparation of the sample, and offer the possibility of continual measurements to describe the effect of hydration [50, 51], drying [52], or permeability [53]. For the measurement of electrical impedance, an automated program was used that measured the electrical resistance of the concrete between two steel rods at a given interval [54]. Samples were prepared using the method explained in section 2.6.4. All samples were connected to the measuring system as shown in Figure 2.11 and measurements were started immediately after casting the samples, and ran every fifteen minutes for one week.

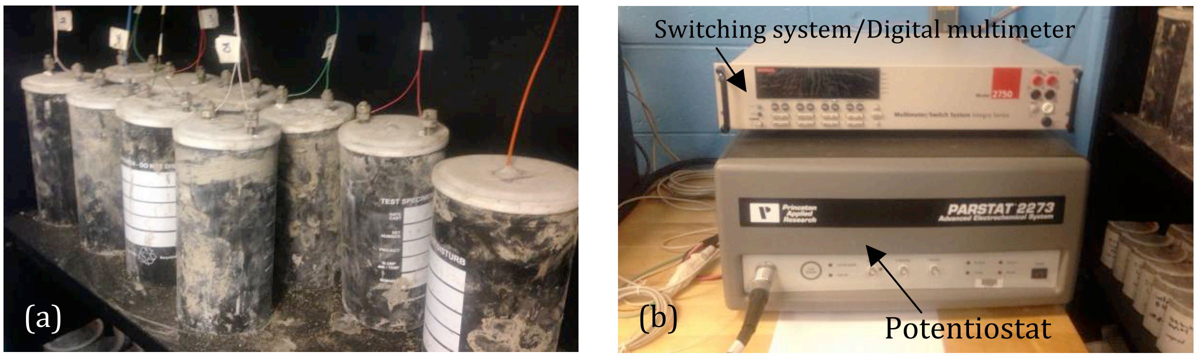

Figure 2.11: (a) Cylinders for the electrical impedance measurement and, (b) Potentiostat and switchboard

The measurement frequency range that was used for the tests ranged from 1 MHz to 10 Hz with ten measurements per decade using the 500 mV AC stimulus. To determine the resistivity of the material, the bulk resistance (R_b) obtained from the impedance response normalized for the effects of specimen and electrode geometries, using the following equation:

$$\rho = R_b/k \qquad \text{Equation 2.9}$$

Where: ρ is the resistivity ($\Omega \bullet m$) of the paste, R_b is the measured bulk resistance (Ω) and k is a geometry factor.

The geometry factor was determined by filling the molds with the concrete simulated pore solution with known resistivity and measuring the bulk resistance between the electrodes. In this experiment the resistivity of the simulated concrete pore solution was measured using a container with known geometry as shown in Figure 2.12. By using this information, the value of the geometry factor, k, was calculated to be 1.144/m for the molds being used in this study.

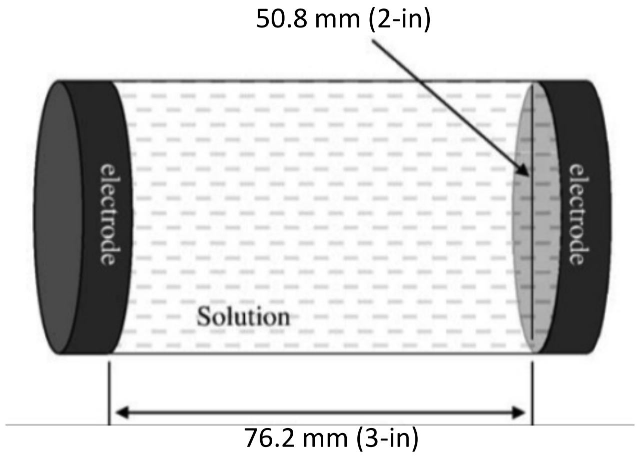

Figure 2.12: Schematic view of the container with known geometry, to measure the resistivity of the solutions

Chapter 3

Results and discussion

3.1 Physical Properties of Coarse Aggregates

The results of standard test methods [38-40] performed on the coarse aggregates to determine the physical properties are presented in Table 3.1 and Table 3.2.

Table 3.1: Physical Properties of Coarse Aggregates

Test Result \ Aggregate	Natural Aggregate	Brick Aggregate
Cold Water Absorption, %	0.95	1.79
Boiling Water Absorption, %	--	1.80
Bulk Specific Gravity	2.46	2.31
Bulk Specific Gravity, SSD	2.48	2.40
Apparent Specific Gravity	2.52	2.54

Table 3.2: L.A. Abrasion results for Coarse Aggregates

Test Result \ Aggregate	Control	25% Brick Aggregate	50% Brick Aggregate	100% Brick Aggregate
L.A. Abrasion Loss, %	64.5	49.3	43.2	30.6
L.A. Abrasion Hardness	0.35	0.25	0.26	0.26

By comparing the absorption values of the two types of aggregates, it can be determined that the crushed brick aggregate, which has nearly twice the absorption of natural aggregates, is more porous. This is also apparent when the specific gravities of the two aggregates are compared.

Additionally, when the L.A. abrasion results are compared, it can be seen that with an increase of percentage of brick aggregate, there is a decrease in overall mass loss. It can be seen that after the addition of 25% brick aggregate, there is a decrease in the hardness ratio of 0.1, with no significant change with the addition of more brick. A lower hardness ratio correlates to an aggregate with a more uniform hardness. In this respect, brick aggregates have a more uniform hardness than natural aggregates from the upstate region of South Carolina.

3.2 Concrete Physical Properties

3.2.1 Workability

The workability of the fresh concrete was determined by the slump test. The results of the slump test are provided in Table 3.3. As can be seen, with a constant water to cement ratio, the workability of concrete increases with an increase in the amount of brick coarse aggregate.

Table 3.3: Slump results

Mixture	**Slump, mm (in)**
Control	44.45 (1.75)
25% Brick	63.5 (2.5)
50% Brick	88.9 (3.5)

3.2.1 Density, Absorption and Voids

The density, absorption, and voids of the hardened concrete specimens are shown in Table 3.4. From the table, it can be seen that the absorption and percentage of voids in all three sample-types are comparable. Table 3.4 also shows that with an increase in brick content, the density of the concrete decreases.

Table 3.4: Density, absorption, and voids of hardened concrete

Sample Type	Absorption After Immersion (%)	Absorption After Boiling (%)	Bulk Density, Dry lb/in^3 (g/mm^3)	Bulk Density After Immersion lb/in^3 (g/mm^3)	Bulk Desity After Boiling lb/in^3 (g/mm^3)	Apparent Density lb/in^3 (g/mm^3)	Volume of Voids (%)
Control	7%	8%	80.9 (2.24)	86.7 (2.40)	87.1 (2.41)	96.8 (2.68)	16%
25% Brick	7%	7%	78.0 (2.16)	83.5 (2.31)	83.8 (2.32)	92.1 (2.55)	15%
50% Brick	8%	8%	76.2 (2.11)	82.0 (2.27)	82.4 (2.28)	91.4 (2.53)	17%

3.3 Concrete Compressive Strength

The compressive strength test was performed on 4-in × 8-in cylinders at 28-days. The results of these tests are shown in Table 3.5. From Table 3.5, it can be seen that the cylinders containing brick aggregate were slightly stronger on average than the control mix. With the addition of more bricks, 50% compared to 25%, there is a slight increase in strength.

Table 3.5: Concrete Compressive Strength Results

	Control Concrete	25% Brick Concrete	50% Brick Concrete
Sample 1, psi (MPa)	6736 (46.44)	6542 (45.11)	7117 (49.07)
Sample 2, psi (MPa)	6537 (45.07)	7000 (48.26)	6730 (46.40)
Sample 3, psi (MPa)	6621 (45.65)	7033 (48.49)	7183 (49.53)
Average, psi (MPa)	6631 (45.72)	6858 (47.28)	7010 (48.33)
Deviation from Control, %	0.00	3.42	5.71

3.4 Freeze/Thaw

The change as a percentage of the original modulus of elasticity versus number of cycles for the control samples and 25% samples are shown in Figure 3.8 (a) and (b), respectively. The dashed line represents the 60% of the initial modulus, which is the ASTM failure criterion. None of the samples fail in less than 300 cycles. However, all three 25% brick samples barely passed through all 300 cycles. Since the samples all reached the full 300 cycles, the durability factor is equal to the relative modulus of elasticity. The average durability factor for the control specimens and 25% brick samples are 88 and 76, respectively. Due to technical issues with the freeze/thaw chamber, the results of the test of 50% brick samples are not available.

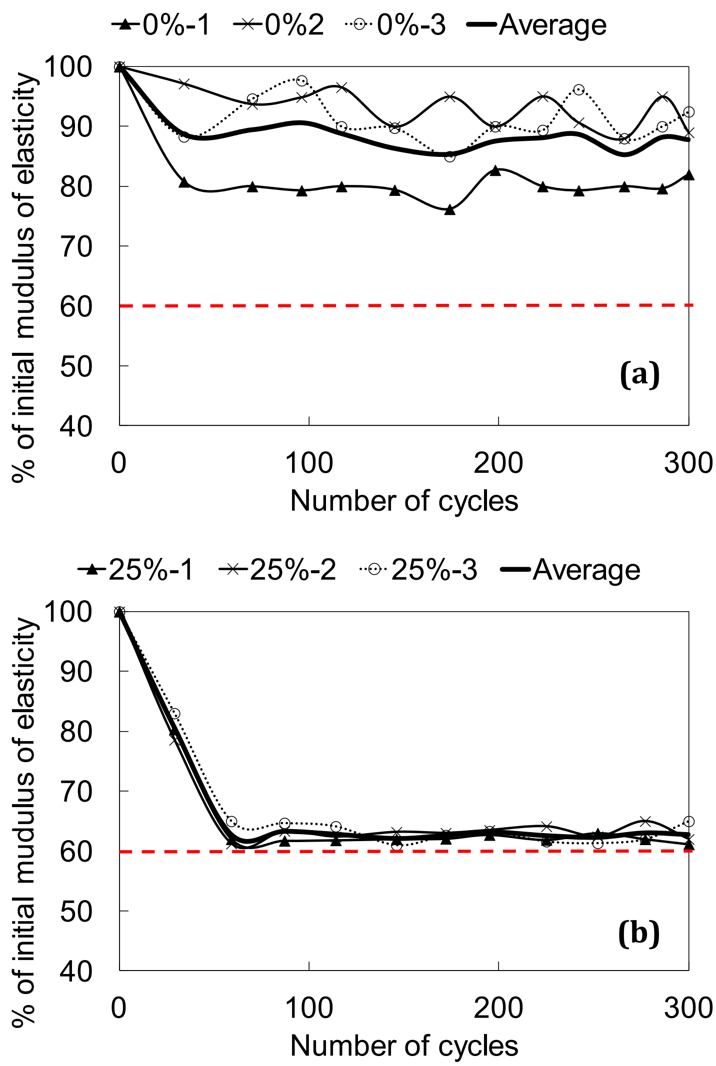

Figure 3.1: Change in modulus of elasticity in (a) control samples and (b) the average change in modulus of elasticity for control samples

3.5 Corrosion

Two different ASTM tests were conducted to determine corrosion characteristics of the different types of concrete mixes. The first test conducted was ASTM G 109, which measures the potential drop between the top rebar and the bottom rebars of the specimens. After taking measurements for this test for five months, no noticeable potential drop, and consequently no current has been able to be obtained, so no conclusions can be drawn from this experiment yet, other than after five months of exposure, all sample types have performed equally well.

The second corrosion test performed was ASTM C876, a measurement of half-cell corrosion potential. Figure 3.2 shows data collected for the first 18-19 weeks (control samples are one week ahead of 25% brick samples, and ten days ahead of 50% brick samples). As can be seen, measurements were performed in both wet and dry cycles to investigate the impact of these cycles on the corrosion half-cell potential. However, these variations are negligible and it can be concluded that no deteriorative corrosion activity is happening on the steel bars. This could be attributed to the fact the chlorides have not reached the surface of steel yet. This hypothesis is confirmed by the results obtained from the chloride penetration test, which will be explained in next section.

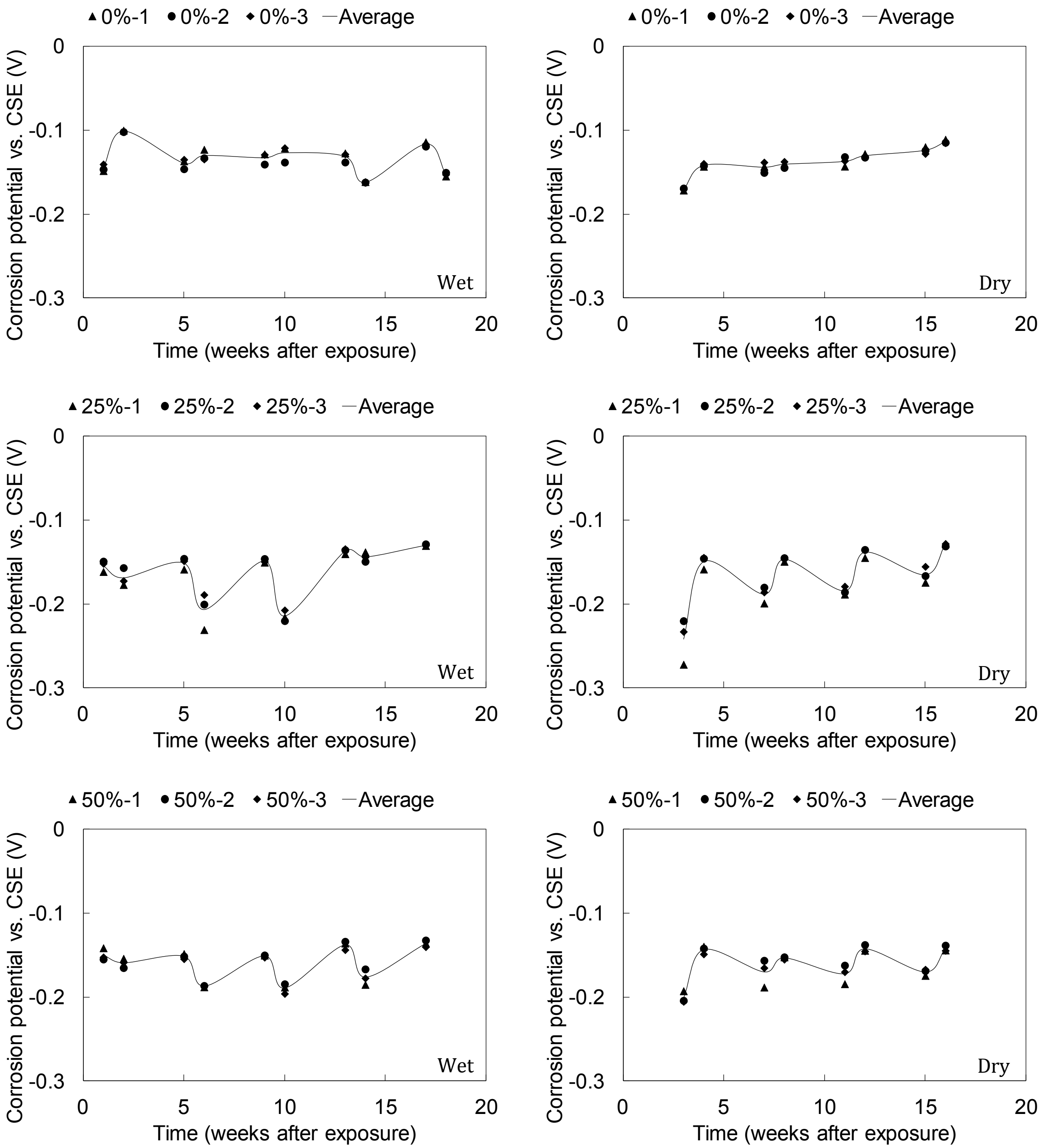

Figure 3.2: Half-cell corrosion potential of control samples, 25% brick samples and 50% brick samples in wet and dry cycles

3.6 Chloride Penetration

By cycling the chloride penetration samples at the same rate as the corrosion samples, it is possible to get an estimation of chloride ingress into the corrosion samples. After splitting the cylinders and spraying the surface with 0.1 N silver nitrate solution, the depth of chloride penetration into the samples was measured. The sprayed samples of each mix can be seen in Appendix A. The average depth of penetration over time for the three sample types is summarized in Figure 3.3. The red dashed line represents the concrete cover depth in G109 samples. As can be seen, the chlorides have not reached the surface of the steel rebars yet which is in agreement with the results of both corrosion measurement tests. As can be seen, chloride penetration increases by increasing the brick content.

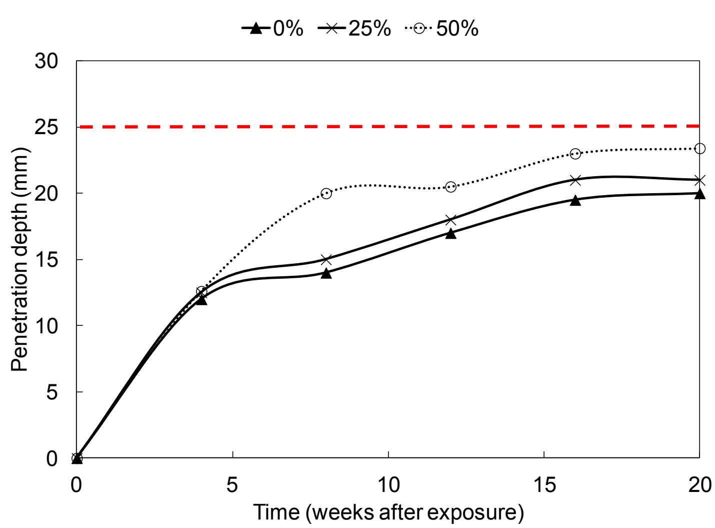

Figure 3.3: Chloride penetration over time

3.7 Electrical Impedance

Figure 3.4 shows the change in electrical resistivity of the average of each of the concrete mixture types, measured for two months. As can be seen, by increasing the brick content, the electrical resistance of the samples decreases. This can be attributed to higher porosity in the samples with brick. This observation is in agreement with the chloride penetration and absorption tests.

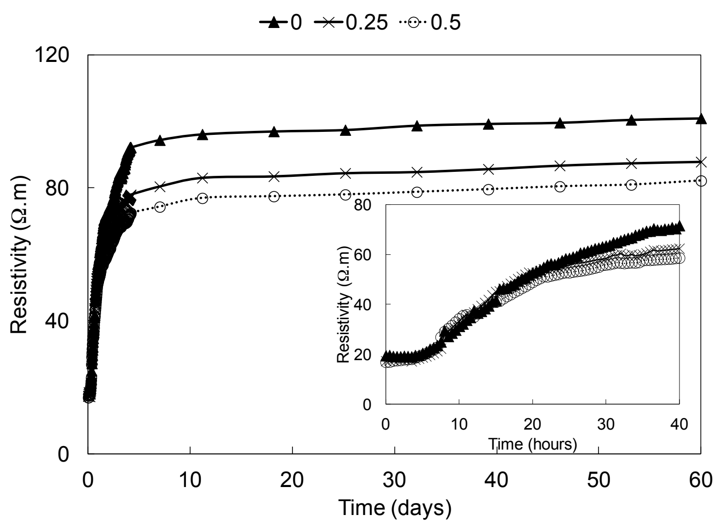

Figure 3.4: Electrical resistivity of concrete over time

Chapter 4

Summary of the Results, Conclusions and Future Works

4.1 Summary of the Results

Based on the data and results found in the comparative study between natural coarse aggregate concrete, 25% brick aggregate concrete, and 50% brick aggregate concrete, the following conclusions can be made:

1. Brick aggregates have a higher porosity and absorption than natural granite aggregates, thus precautions need to be made when mixing to account for the change in water demand.
2. Brick aggregate concrete has an increased workability compared to granite aggregate concrete, with the workability increasing with an increase in coarse brick aggregate content.
3. Brick aggregate concrete, using 25% brick and 50% brick replacement of natural coarse aggregates, show higher compressive strength than concrete made with 100% granite aggregates.
4. By increasing the brick content, the resistance to chloride penetration decreases. This could be attributed to the higher porosity and absorption in bricks compared to those in natural aggregates.
5. After six months of exposure, none of the corrosion samples show any indication of the initiation of corrosion. This is because the chlorides have not reached the surface of steel in none of the samples.

6. Both the control specimens and the 25% brick specimens were able to pass the full 300 cycles of the freeze/thaw tests. However, the 25% brick barely pass the tests. The control had an average durability factor of 88 and the 25% brick samples had an average durability factor 76.
7. The electrical resistivity changes between the three types of concrete, with the control having the highest resistivity and the 50% brick having the lowest resistivity. As it was expected, this correlates to an inverse relationship with the porosity of the concrete samples and chloride penetration test. After more information is found from the corrosion specimens, a correlation should be found with these results as well.

4.2 Conclusions

Based on the obtained results, it is obvious that just focusing on the mechanical or workability performance of the concrete made with crushed bricks as aggregates is not a correct approach. Durability of concrete involves broader aspects, which need to be considered. Based on this study, concrete made with crushed brick aggregates compared to concrete made with natural aggregates exhibit poorer performance.

In general, increasing brick content, without any other modification, have negative impact on the durability of concrete which includes: absorption, chloride penetration, and electrical resistivity. It should be emphasized that the granite natural aggregates used in this study are not necessarily the highest quality aggregates, and concrete made with higher quality natural aggregates could potentially exhibit better performance over the concrete made with crushed bricks as partial aggregates.

4.3 Future Works

1. The corrosion samples should continue to be monitored with weekly readings and their results compared with other results found in this thesis for possible correlations.
2. After corrosion is observed, other corrosion tests such as cyclic voltammetry, cyclic polarization and linear polarization resistance should be carried out on the steel bars to more precisely investigate the corrosion process.
3. The performance of concrete with more brick replacement up to 100% should also be investigated.
4. To practically be more realistic, instead of using just one size of aggregates, aggregate gradation should also be investigated.
5. Addition of supplementary cementitious materials such, fly ash, to concrete mixtures containing brick aggregates should be studied. This might minimize some of the negative impacts of bricks, such as the possible effect of the aggregate on the formation of the interfacial transition zone, and consequently improve the durability of concrete made with crushed bricks aggregates.
6. Due to the results from absorption, chloride penetration and the electrical resistance test, it seems that the different corrosion products with different morphology might be formed on the surface of the rebar. Therefore, it is

important to perform spectroscopic analysis to reveal these possible dissimilarities.

7. Microstructure of the concrete made with brick aggregates needs to be investigated and compared to that of concrete made with natural aggregate. This will reveal the possible differences in the Interfacial Transition Zones (ITZ) among different samples.
8. For future studies, the performance of concrete made with brick from demolition waste from various sources should be examined.

Appendices

Appendix A: Cross Section of the Specimens Exposed Chlorides and Sprayed With AgNO3

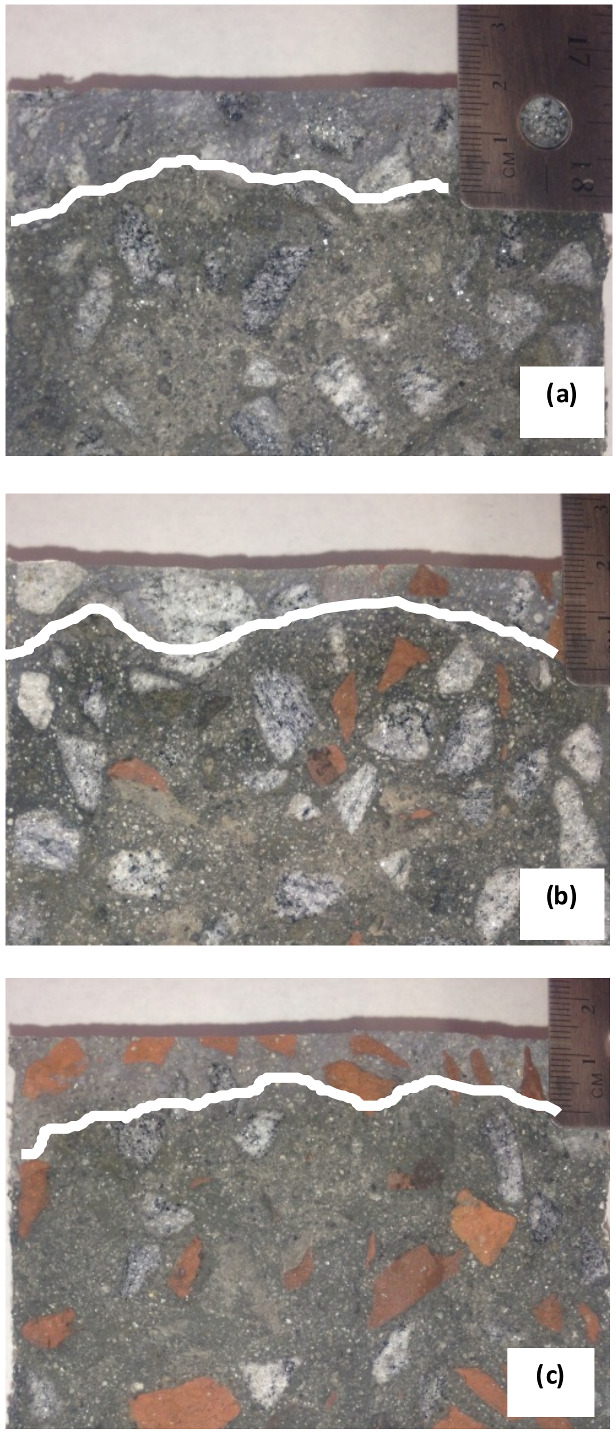

Figure A.1. Chloride penetration after one month in (a) Control, (b) 25% Brick, and (c) 50% Brick

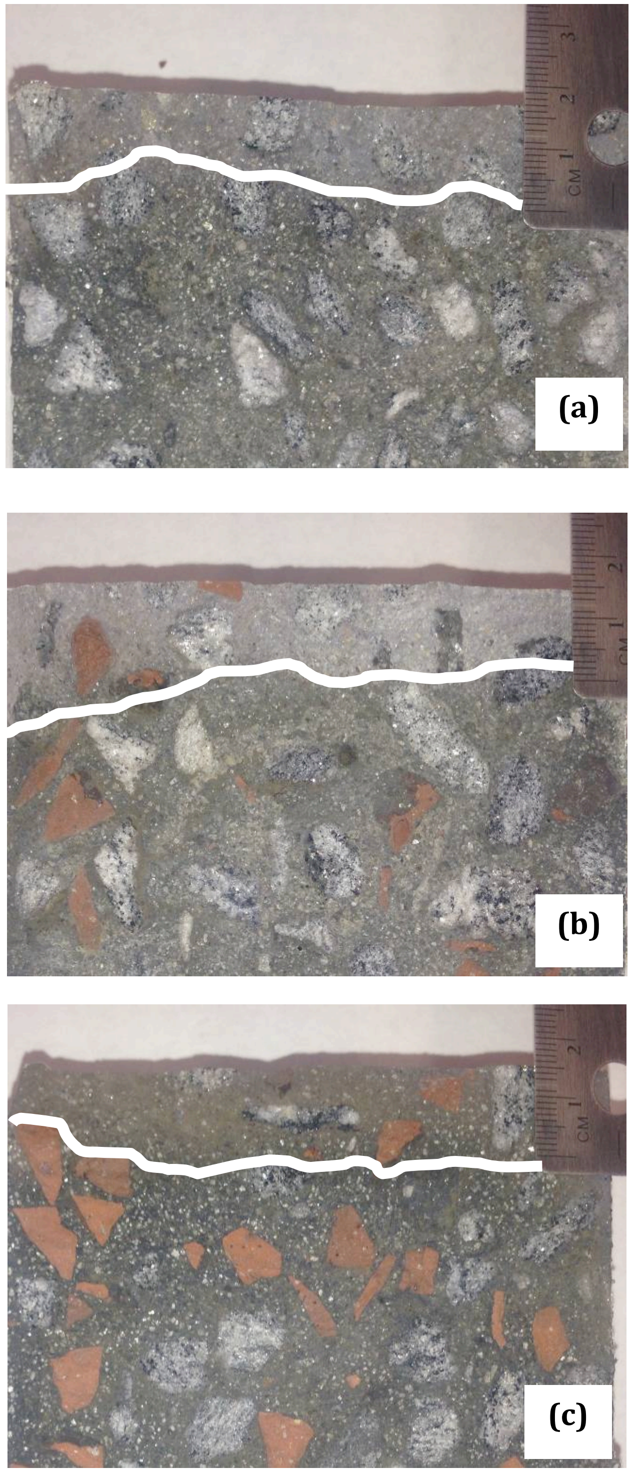

Figure A.2. Chloride penetration after two months in (a) Control, (b) 25% Brick, and (c) 50% Brick

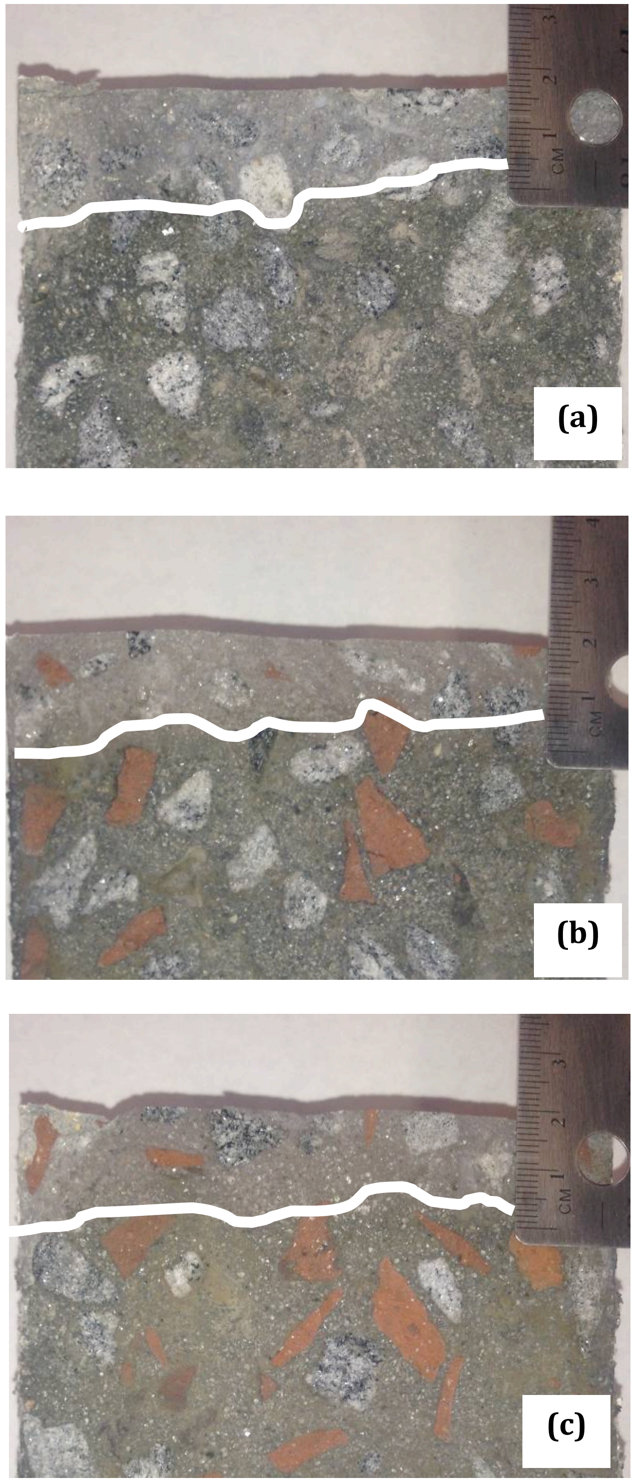

Figure A.3. Chloride penetration after three months in (a) Control, (b) 25% Brick, and (c) 50% Brick

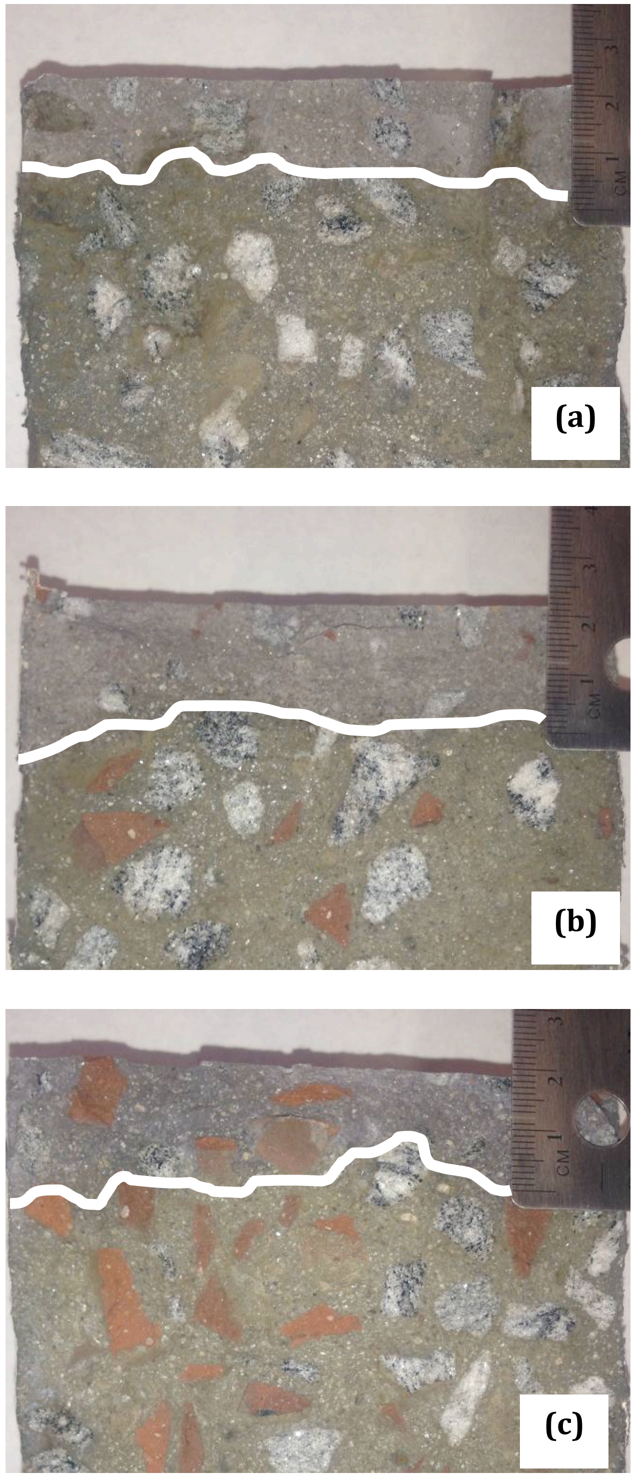

Figure A.4. Chloride penetration after four months in (a) Control, (b) 25% Brick, and (c) 50% Brick

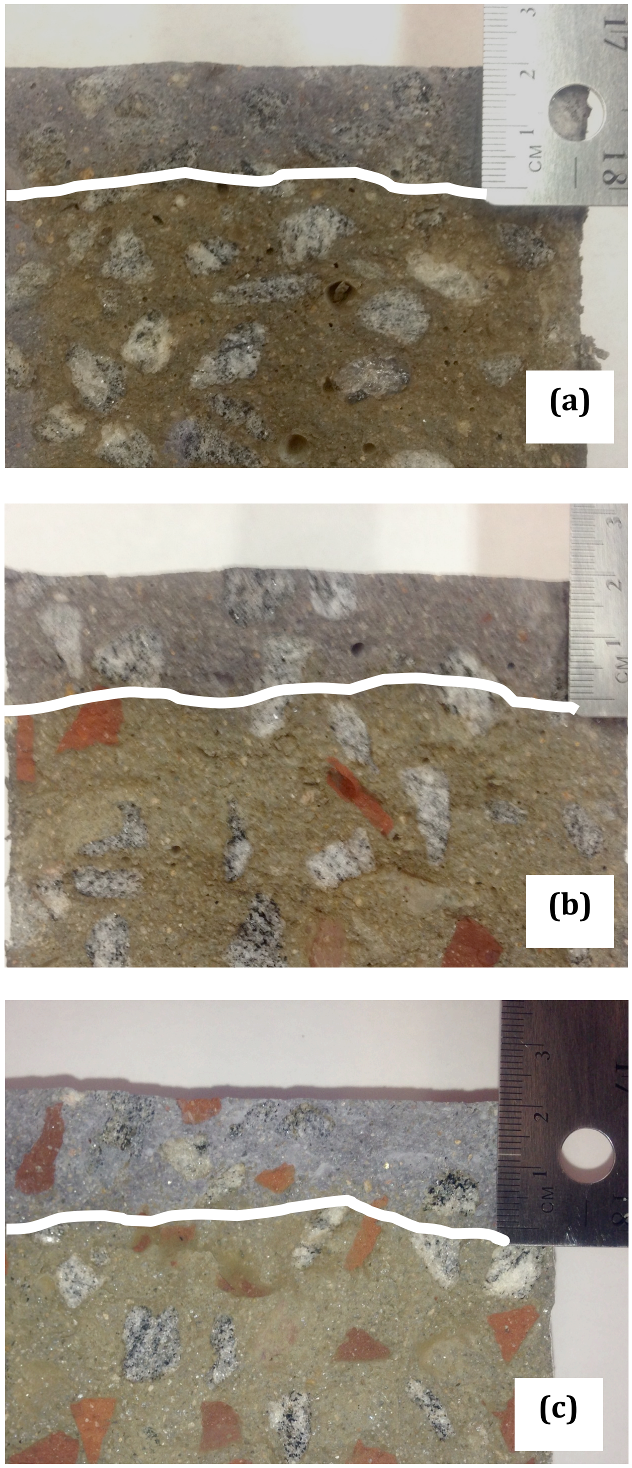

Figure A.5. Chloride penetration after five months in (a) Control, (b) 25% Brick, and (c) 50% Brick

Appendix B: Cement Mill Test Report

ARGOS

Cement Mill Test Report

Month of Issue: December 2011

Plant:	Harleyville, South Carolina
Product:	Portland Cement Type I and Type I/II
Silo:	Bagged
Manufactured:	November 2011

ASTM C150-11 and AASHTO M85-11 Standard Requirements

CHEMICAL ANALYSIS

Item	Spec limit	Test Result
Rapid Method, X-Ray *(C114)*		
SiO2 (%)	---	20.6
Al2O3 (%)	6.0 max	5.1
Fe2O3 (%)	6.0 max	3.4
CaO (%)	---	64.5
MgO (%)	6.0 max	1.0
SO3 (%)	3.0 max *	3.1
Loss on ignition (%)	3.0 max	1.1
Insoluble residue (%)	0.75 max	0.25
Adjusted Potential Phase Composition*(C150)*		
C3S (%)	---	58
C2S (%)	---	16
C3A (%)	8 max	8
C4AF (%)	---	10

PHYSICAL ANALYSIS

Item	Spec limit	Test Result
Air content of mortar (%)*(C185)*	12 max	7
Blaine Fineness (m2/kg) *(C204)*	280 - 430	391
-325 (%) *(C-430)*	---	97.6
Autoclave expansion (%)*(C151)*	0.80 max	0.03
Compressive strength (MPa, [PSI])*(C109)*		
1 day	---	17.2 [2490]
3 days	12.0 [1740] min	27.8 [4030]
7 days	19.0 [2760] min	34.9 [5070]
28 days (Reflects previous month's data)	---	45.1 [6540]
Time of setting (minutes)		
Vicat Initial *(C191)*	45 - 375	102
Mortar Bar Expansion (%) (C1038)**	0.02 max	0.01

ASTM C150-11 and AASHTO M85-11 Optional Chemical Requirements:

Item	Spec limit	Test Result
NaEq (%)	0.60 max	0.49

* May exceed 3.0% SO3 maximum based on our C1038 results of <0.02% expansion at 14 days.

** Current Production run not available - most recent provided. "na" = not applicable.

ASTM C150-11 & AASHTO M85-11 STANDARD SPECIFICATIONS FOR TYPE I AND TYPE I/II CEMENT;
ASTM C150-11 & AASHTO M85-11 OPTIONAL CHEMICAL REQUIREMENTS FOR TYPES I & I/II LOW ALKALI CEMENT.

Certified By:

Sean J. Makens

Sean J. Makens - Process & Quality Mgr
Report created: 12/9/2011

Argos USA - Harleyville Plant
463 Judge Street, Harleyville, South Carolina 29448
Phone: 843-462-7651

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